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Quality of energy resulting from association converter- machine for the electric drive of a system of wind generation

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Abstract: The work presented in this paper concerns, the quality of energy negated with wind power system, we were interested initially to impact of the choice of the type of PWM control of the converters on the output quality of energy and we were interested to the feeding and controls of doubly fed induction generator (DFIG) and the contribution which it will be able to carry its application in a wind chain conversion. The modeling of DFIG was presented, thus we applied the vector control in active and reactive generator power. Then we are interested in cascades based on a DFIG and back-to-back converter. The results obtained with simulation allowed the performance evaluation of the application of the asynchronous machine double power supply in the wind field.

Keywords: Quality of energy, Wind energy, doubly fed induction generator**,** Buck to buck converter. Pulse width modulation PWM

1. INTRODUCTION

The current energy context, characterized by the impoverishment of the reserves of energy fossil, the warming of planet partly due to the gas emission with greenhouse effect and the concept of sustainable development, causes the rise of alternative energy solutions. To produce clean energy became a challenge for everyone.

Among the solutions with this worldwide problem, it there with energy production of the wind type. The quality of the energy produced by the wind generators and their impact on the electrical communication as well as the output of the latter remains a concern major for this type of renewable energy like for the other types of renewable energies. The interest carried to the asynchronous generator with double fuel supply (GADA) does not cease growing especially in the field of renewable energies. Indeed, in the wind field, the GADA presents many advantages: the converter related to the rotor reinforcement is dimensioned with the third of the rated power of the rotor, the fact of using a space vector PWM with an optimization of commutation in the semiconductors reduces to us of half the losses by commutation, for the same spectrum. The use of the static converters in the installations of conversion of electrical energy takes part to deteriorate the quality of the current and the tension of the distribution networks because of the harmonics which they generate. Indeed, these systems consume non sinusoidal currents, the article presents a synthesis of the techniques of modulation of width of impulse (PWM), classified as a solution of this problem, applied to the converters of the chain rotor made up of two converters of power, one functioning like of rectifier with unit power-factor and the other like of inverter.

Two techniques of PWM are studied in this work, sinus- triangle PWM, space vector (SVPWM). The converter being not on the main path of the power flow, it is designed in the vicinity of 30% to recover a 30% of stator power while working in generating mode [3]. Connected to the rotor power converter is used for the management of active and reactive power of the machine.

The control of the rotor voltages can influence the magnetic field inside so the machine may operate in either motor or generator modes, in both hypo- and hyper-synchronous zones. The overall structure of wind power generation system is shown in Fig. 1. This configuration makes it possible to impose on the load (network) currents displaying a low harmonic distortion and thus results in producing energy of better quality.

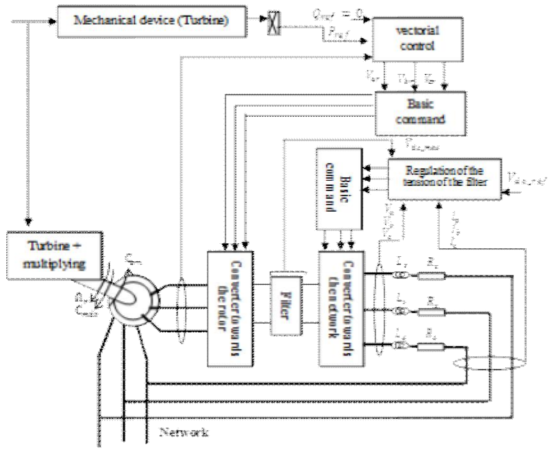

Fig. 1 Structure of the overall wind power system.

2. ROTOR CHAIN MODEL

Figure 2 represents the rotor chain (rectifier - inverter).

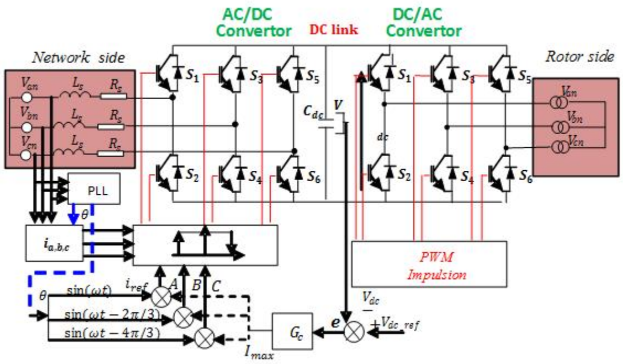

Fig. 2 Chain rotor: Rectifier-Inverter « back to back »

The static converter connected to the rotor of the machine (inverter structure) is used for the management of the active and reactive powers of the machine. The role of the static converter connected to the network (rectifier structure) is to regulate the tension of the continuous link while ensuring a unit power-factor of the AC side.

2.1 Inverter

The basic structure of such a three-phase PWM inverter is shown in Fig 2. The connection between the DC side and the AC side via the switches is given by the function (2) and (3). These switches are complementary [9][10], their state is defined by the following function:

$$u_k = \begin{cases} +1, \overline{u_k} = 0 \\ 01, \overline{u_k} = +1 \end{cases}, k = 1,2,3 \quad (1)$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \quad (3)$$

To study the impact of the PWM on power quality and performance, we compared the Space Vector PWM (SVPWM) with sinus triangle PWM.

A. Principle of sinus-triangle modulation

Figure 3 shows the model of a single-phase inverter with a midpoint grounded continuous side that acts as a capacitive divider. Figure 4 illustrates the principle of the sine-triangle pulse width modulating.

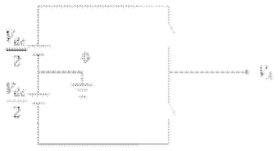

Fig.3 Model of single phase Inverter with a midpoint

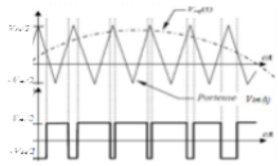

Fig.4 Principle of sine-triangle Pulse width modulation

The inverter output voltages are determined as follows:

- When: $V_{ref} > V_{tri}$, $V_{A0} = V_{dc}/2$;
- When : $V_{ref} < V_{tri}$ $V_{A0} = -V_{dc}/2$.

Sinus-triangle PWM is Characterized by:

- Index of modulation, $m = f_s / f_1$,

  f_s: est la fréquence de la porteuse (V_{tri}).

  f_1: est la fréquence de la tension de référence ($V_{réf}$).

- Voltage ajustement coefficient $r = \frac{V_{ref}}{V_{tri}} = \frac{\max(V_{Ao})_1}{V_{dc}/2}$, $(V_{A0})_1$ is the fundamental of V_{A0}.

B. Príncíple of the SVPWM

This space vector PWM is not based on the separated calculations for each arm of the inverter, but on the determination of a total approximated vector of control over one period of modulation T_m. This modulation is used by the modern controls AC machines**.**

There are eight possible combinations of the six states of open or closed switches. According to the two equations (2) and (3), we can deduce the possible eight control vectors [2][5].

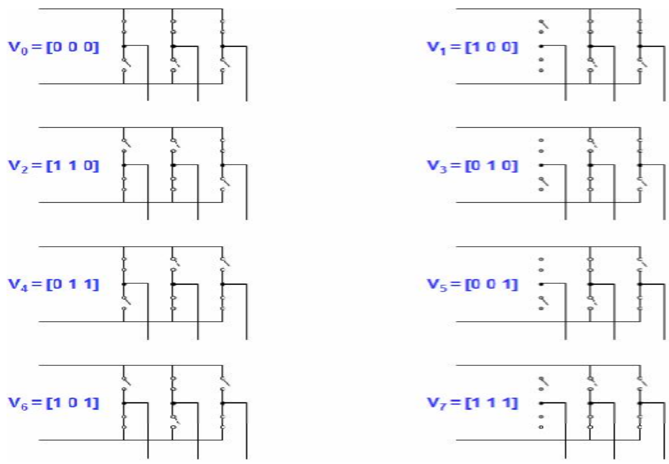

Fig. 5 The eight vectors of command *(V_0 to V_7).*

The six non-zero control vectors form a hexagon in the $(\alpha\beta 0)$ frame (Fig. 6). The angle between two adjacent vectors is $\pi/3$. The two zero vectors (*V_0* and *V_7*) are at (coincide with) the origin and imposes a zero voltage to the load. The vectors are referred to as the eight space vectors, and are rated: *V_0, V_1, V_2, V_3, V_4, V_5, V_6, V_7.* An appropriate switching between each two space vectors can be applied to the output voltage in order to get a desired reference voltage V_{ref} in the ($\alpha\beta 0$) frame [2][5][7].

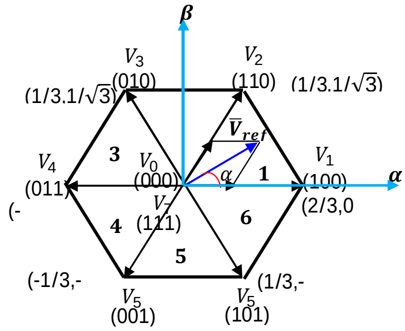

Fig. 6 Representation of eight voltage space vectors.

C. Study of the frequential spectrum

The rate of harmonic distortion and the power-factor are employed respectively to quantify the harmonic disturbances and the consumption of reactive power. Two rates of harmonic distortion are distinguished:

- Rate of harmonic distortion of the current, noted THD_i ;
- Rate of harmonic distortion of the tension, noted THD_i .

$$THD_i = \sqrt{\sum_{n=2}^{\infty} \left(\frac{I_{cn}}{I_{c2}}\right)^2} \tag{4}$$

I_{cn} : RMS of the row n harmonic of the load current.

I_{c1} : RMS of the fundamental of the load current.

THD_i only depends on the RMS of the load current. However, THD_v is function of the harmonic currents, characteristic of the load, and the short-circuit impedance imposed by the network:

$$THD_v = \sqrt{\sum_{n=2}^{\infty} \left(\frac{V_{cn}}{V_{c1}}\right)^2} = \sqrt{\sum_{n=2}^{\infty} \left(\frac{z^n{}_{scc}}{V_{c1}}\right)} \tag{5}$$

V_{c1}: Is the effective value of v_{c1}

Thus, more impedances $z^n{}_{scc}$ (n>1) are low, more the distortion of the tension is low.

V_{c1} et V_{cn} respectively, designate the voltage at the connection point between the network and the load for the fundamental frequency and harmonic of row η. [15][16]

2.2 Rectifier with unit power factor

PWM voltage rectifier is used in this work is commanded convertor with sinusoidal absorption of current. In this type of converter the constraint of control will be thus to impose that *Q* (reactive power) and the harmonics of currents absorbed by the inverter are null [6]. The main objective of these converters is to correct the power factor of the AC side.

A. The power factor control strategy

Figure 2 represents the schematic diagram of a three-phase rectifier of tension controlled with a PWM current (hysteresis PWM). The control is carried out by measuring the instantaneous currents of phase of such kind, so that they are sinusoidal currents which will be considered as $i_{\_ref}$.

The amplitude of the reference current is calculated as shown in the scheme:

$$I_{\max} = G_c e = G_c (V_{dc\_ref} - V_{dc}) \tag{6}$$

Where G_c is a *PI* corrector designed to get the appropriate reference current [10]. e is the deference between reference DC voltage V_{dc_ref} and actual DC votltage V_{dc} . $I_{\max}$ will be compared between the sine function having the same source frequency and a desired shift angle φ .

The max value which the frequency of this control can reach is given by the following equation:

$$F_s^{\max} = \frac{V_{dc}}{4hL_s} \tag{7}$$

h: is the bandwidth of hysteresis, *PI* corrector parameters are defined as follows [3]:

$$(K_p = K_f,\ \mathrm{K_i} = \frac{K_f}{C_{dc}}) \tag{8}$$

K_f is chosen so that the system behaves as a first order system, C_{dc} is a capacity value of a capacitor of a *DC* link, it served here as a filter.

3. MATHEMATICAL MODEL OF DFIG WIND TURBINE

The wind speed is obtained using the equation (9):

$$V_v(t) = A + \sum_{n=1}^{i} (a_n.\sin(b_n w_v t)) \tag{9}$$

Mechanical power is calculated using the equation (10):

$$P_{méc} = \frac{1}{2} C_P(\lambda,\beta) \rho \pi R^2 V_v^3 \tag{10}$$

Where ρ is the density of air equal to 1.225 kgm $^{-3}$ [4][8][14], R is radius of turbine, V_v speed of the wind, C_P the power coefficient depends on the speed ratio λ and the pitch angle β. The torque produced by the wind turbine is

$$C_t = \frac{P_{méc}}{\Omega_{turbine}} = \frac{1}{2\Omega_{turbine}} C_P(\lambda,\beta) \rho \pi R^2 V_v^3 \tag{11}$$

With $C_T(\lambda,\beta) = \dfrac{C_P(\lambda,\beta)}{\lambda}$ called torque coefficient, with:

$$\lambda = \frac{R\Omega_{turbine}}{V_v} \tag{12}$$

In the *dq* frame linked to the rotating magnetic field for DFIG, the following equations are:

$$\begin{cases} V_{ds} = R_s i_{ds} + \dfrac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \\ V_{qs} = R_s i_{qs} + \dfrac{d\psi_{qs}}{dt} + \omega_s \psi_{ds} \\ V_{dr} = R_r i_{dr} + \dfrac{d\psi_{dr}}{dt} - \omega_r \psi_{qr} \\ V_{qr} = R_r i_{qr} + \dfrac{d\psi_{qr}}{dt} + \omega_r \psi_{dr} \end{cases} \tag{13}$$

$$\begin{cases} P_s = V_{ds} i_{ds} + V_{qs} i_{qs} \\ Q_s = V_{qs} i_{qs} - V_{ds} i_{qs} \\ P_r = V_{dr} i_{dr} + V_{qr} i_{qr} \\ Q_r = V_{qr} i_{qr} - V_{dr} i_{qr} \end{cases} \tag{14}$$

$$\begin{cases} \psi_{ds} = L_s i_{ds} + M i_{dr} \\ \psi_{qs} = L_s i_{qs} + M i_{qr} \\ \psi_{dr} = L_r i_{dr} + M i_{dr} \\ \psi_{qr} = L_r i_{qr} + M i_{qr} \end{cases} \tag{15}$$

According to the fundamental law of dynamics we can write:

$$C_{em} = C_r + f\Omega_{méc} + J\frac{d\Omega_{méc}}{dt} \tag{16}$$

With the expression of the electromagnetic torque C_{em} as a function of rotor current and stator flux:

$$C_{em} = p\frac{L_{sr}}{L_s}(\psi_{qs} i_{dr} - \psi_{ds} i_{qr}) \tag{17}$$

Here R_s, R_r are stator and rotor active resistances, L_s, L_r, L_{sr} are respectively stator, rotor and mutual inductances, i_{ds}, i_{qs}, i_{dr}, i_{qr} are respectively stator and rotor currents in the dq frame. ω_s speed of stator magnetic field, ω_r angular speed of rotor, P_s, Q_s, P_r, Q_r are respectively stator and rotor active and reactive powers, V_{ds}, V_{qs}, V_{dr}, V_{qr} are respectively stator and rotor voltage components in the dq frame, p number of pair pole, C_r constant torque, f Coefficient of friction, J overall inertia of the turbine plant (turbine, mechanical gear, DFIG), C_{em} electromagnetic torque, Ω_{em} mechanical rotor speed. [1][2][13]

4. VECTOR CONTROL OF DFIG

A vector control part is needed so that one of the dq components have to be eliminated in order improves output quality, but also to get a maximum desired power. Both targets can be achieved by correctly designing PI Controllers. By choosing a reference two-phase dq linked to the rotating field, and aligning the stator flux vector ψ_s with the axis d, $\psi_{qs}=0$, $\psi_{ds}=\psi_s$. The expression of the electromagnetic torque becomes:

$$C_{em} = -p\frac{L_{sr}}{L_s}\psi_{ds}i_{qr} = -p\frac{L_{sr}}{L_s}\psi_s i_{qr} \tag{18}$$

Assuming that flux ψ_{ds} is kept constant (which is ensured by the presence of a stable network connected to the stator [11][12][13], the choice of this frame makes the electromagnetic torque produced by the machine, therefore the active power, only rotor q axis current dependent. Neglecting the resistance of the stator winding R_s **,** equation (13) becomes:

$$\begin{cases} V_{ds} = 0 \\ V_{qs} = V_s = \omega_s\psi_s \\ V_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_r\psi_{qr} \\ V_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_r\psi_{dr} \end{cases} \tag{19}$$

The rotor flux is then written as follows:

$$\begin{cases} \psi_{dr} = (L_r - \frac{M^2}{L_s})i_{dr} + \frac{MV_s}{\omega_s L_s} \\ \psi_{qr} = (L_r - \frac{M^2}{L_s})i_{qr} \end{cases} \tag{20}$$

With ψ_{dr} ψ_{qr} that in equation (20) put in equation (19) we obtain steady state equations as:

$$\begin{cases} V_{dr} = R_r i_{dr} - g\omega s(L_r - \frac{M^2}{L_s})i_{qr} \\ V_{qr} = R_r i_{qr} + g\omega_s(L_r - \frac{M^2}{L_s})i_{dr} + g\omega_s\frac{MV_s}{\omega_s L_s} \end{cases} \tag{21}$$

The stator active and reactive powers are then:

$$\begin{cases} P_s = -V_s\frac{M}{L_s}i_{qr} \\ Q_s = \frac{V_s\psi_s}{L_s} - \frac{V_s M}{L_s}i_{dr} \end{cases} \tag{22}$$

Approximating ψ_s by $\frac{V_s}{\omega_s}$, Q_s expression becomes:

$$Q_s = \frac{V_s^2}{L_s\omega_s} - \frac{V_s M}{L_s}i_{dr} \tag{23}$$

To achieve these objectives PI correctors are used, and the desired active and zero reactive powers to the network is imposed in order to obtain both maximum power and a unity power factor. The overall desired (reference) turbine power is less than this optimal and imposed as it is known by the efficiency η of the overall turbine plant [4].

$$P_{g\_réf} = \eta P_{méc\_opt} \qquad (24)$$

$$P_{méc\_opt} = \frac{1}{2} C_{p\_\max} \rho \pi R^2 V_v^3 \qquad (25)$$

$P_{méc\_opt}$: The optimal mechanical power.

The gains of correctors K_p , K_i are calculated based on the parameters of the machine and the response time τ_r [3].

$$K_p = \frac{1}{\tau_r} \frac{L_s (L_r - \frac{M^2}{L_s})}{M V_s} \qquad (26)$$

$$K_i = \frac{1}{\tau_r} \frac{R_r L_s}{M V_s} \qquad (27)$$

5. SIMULATIONS RESULTS AND DISCUSSION

Simulation results with SVPWM

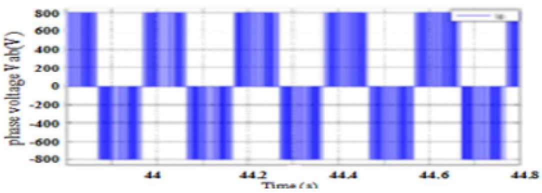

Fig. 7.a Phase voltage Vab (V)

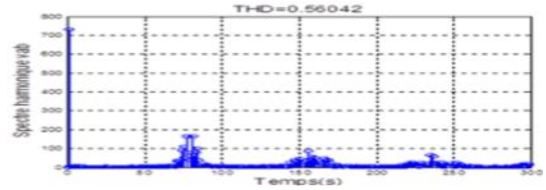

Fig. 7.b harmonic spectrum of the phase voltage Vab (V)

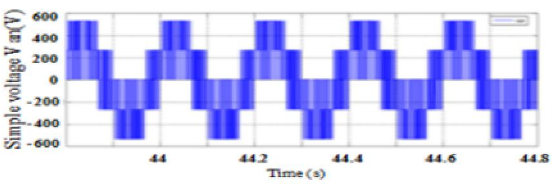

Fig. 7.c Simple voltage Vab (V)

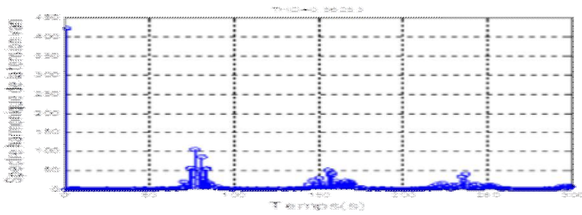

Fig. 7.d Harmonic spectrum of the simple voltage Vab (V)

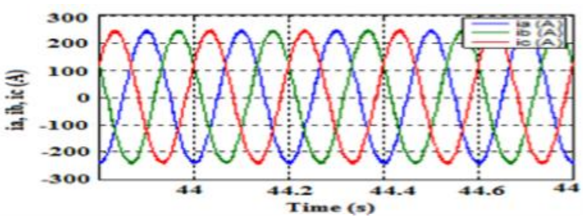

Fig. 7.e Currents at the Output of converter

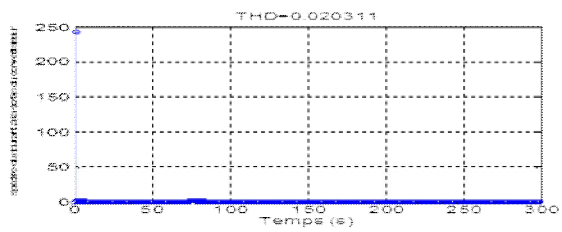

Fig. 7.f Harmonic spectrum of the Currents at the Output of converter

Simulation results with Sinus-Triangle PWM

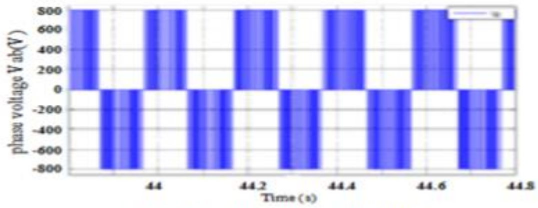

Fig. 8.a Phase voltage Vab (V)

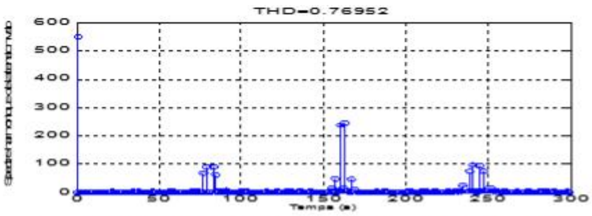

Fig. 8.b Harmonic spectrum of the phase voltage Vab (V)

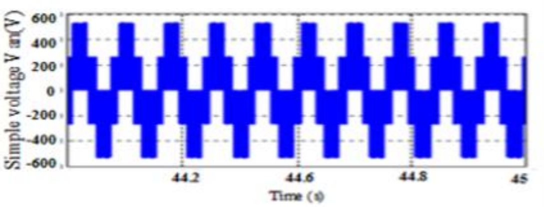

Fig. 8.c Simple voltage Vab (V)

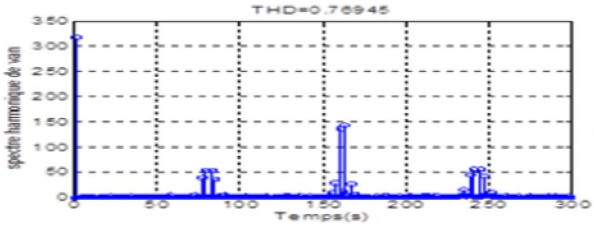

Fig. 8.d Harmonic spectrum of the simple voltage Vab (V)

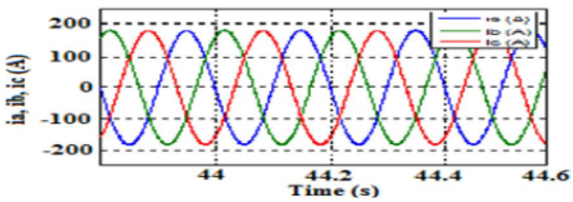

Fig. 8.e Currents at the Output of converter

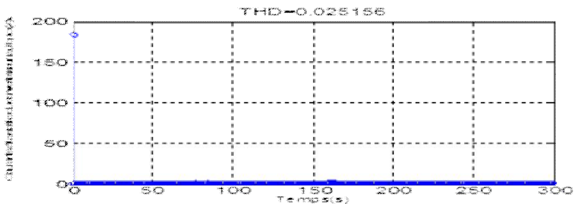

Fig. 8.f Harmonic spectrum of the Currents at the Output of converter

Simulation results are summarized in the following table:

Table 1 Model parameters

PWM	Phase voltage Vab		Out put current ia	
	amplitude	*THD*	*amplitude*	*THD*
SVPWM	730 V	0.56042	249 A	0.0203
sinus_triangle PWM	550 V	0.7695	158 A	0.0251

Simulation results of the aero-generator system

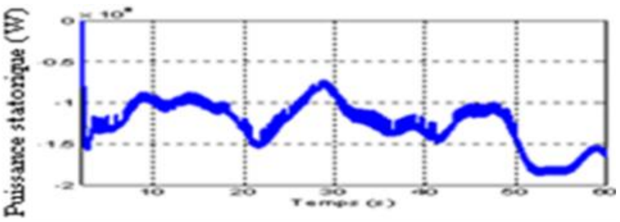

Fig. 10. Stator active power (*W*)

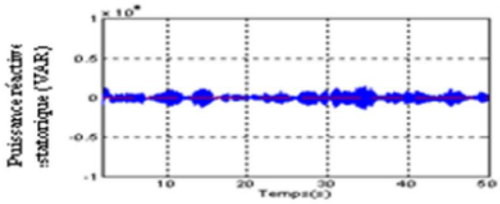

Fig. 11. Stator reactive power (*VAR*)

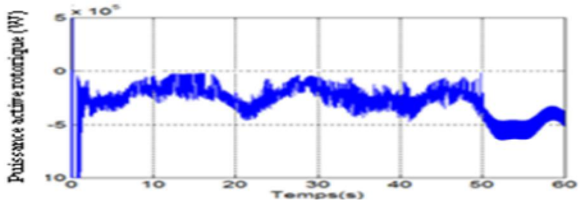

Fig. 12. Rotor active power(*W*)

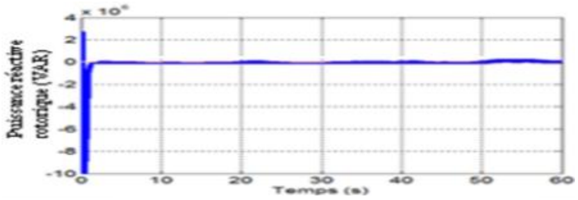

Fig. 13. Rotor reactive power (*VAR*)

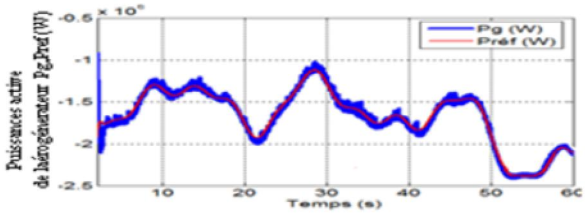

Fig. 14. Overall generator active power (*W*)

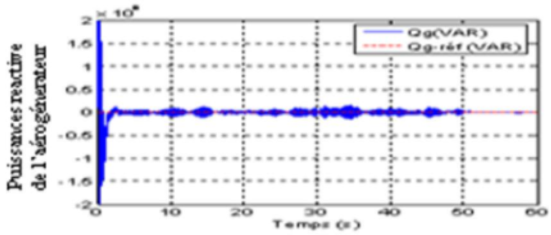

Fig. 15. Overall generator reactive power (*VAR*)

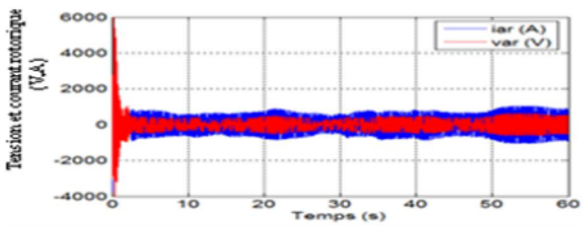

Fig. 16. Rotor current(*A*) and voltage(*V*) (phase a)

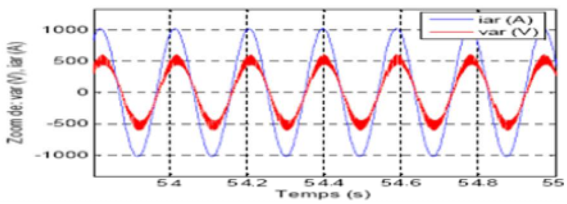

Fig. 17. Zoom of rotor current and voltage

After simulation of two techniques of modulation SVPWM and sinus triangle, we obtained the results shows in Fig. (7a-7f) and Fig. (8a-8f), we note that for the same sampling rates the space vector PWM gives better results on the values plan of fundamental and the harmonic level after the spectral analysis, to add to that, times of simulation are reduced by using the SVPWM. Figures 10 and 11 shows the active and reactive power produced by the stator of the machine. The power with a negative sign clearly justifies the stator is generating energy. Figures 12 and 13 shows the active and reactive power respectively from the rotor side. The power is transmitted from the rotor to the network, testifying the specific advantage of a DFIG that can generate energy, in the contrary from an ordinary induction machine which consume energy, from rotor. The above power figures show that outputs fully follow desired references and the correctors has been successfully designed. For all reactive components the powers follow the zero reference. This mean that the energy quality of the network would improve and have no distortion. The overall active and reactive power, produced by the wind turbine, that are the sum of stator and rotor ones are shown in Fig.14 and Fig.15. Figure 16, shows the shape of the rotor voltage and current. Figure 17 shows the shape, by zooming, of the overall voltage and current of the wind turbine. The phase shift between these two quantities is clearly zero (φ=0) this means a good quality of generated energy and the absence of distortion in the grid side.

6. CONCLUSION

In this paper we have modeled and simulated different parts of wind power plant. The combination of a back to back converter with DFIG rotor allowed us to control the flow of rotor power and keep a unity power factor. These different results are given for operation in hyper synchronous generator mode and got a good track to all set references.

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